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ANNUAL TECHNICAL REPORT

Bureau of Mines In-House Research

Prediction of Geologic and Hydrologic Conditions
Ahead of a Rapid Excavation Operation

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13. ABSTRACT

A well logging system for making measurements of physical properties of rock penetrated by vertical drill holes was designed and partially developed by adapting on-hand Bureau of Mines equipment to special needs of geological-hydrological prediction problems associated with tunneling at depths of several thousand feet in hard rock. Calibration holes and models were developed for providing a means of improved quality control required for the quantitative measurements of interest. A new interpretive technique for determining P- and S-wave velocities from acoustic logs was developed and preliminary tests were performed to evaluate its effectiveness.

The objective of this project is to develop new or improved techniques of geophysical well logging and cross-hole measurements to determine geologic and hydrologic conditions in advance of rapid excavation tunneling in hard rock environments at depths of several thousands of feet.

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PREDICTION OF GEOLOGIC AND HYDROLOGIC CONDITIONS AHEAD OF RAPID EXCAVATION OPERATIONS

Technical Report Summary

Objective: The objective of this project is to develop new or improved techniques of geophysical well logging and cross-hole measurements to determine geologic and hydrologic conditions in advance of rapid excavation tunneling in hard rock environments at depths of several thousands of feet.

Research Plan: During the first year, just completed, emphasis was placed on designing, developing and calibrating a mobile geophysical well logging unit to be tested for use in vertical drill holes along the line of a tunnel. The development of this well logging capability will be extended into the coming project year, and in addition, techniques for making cross-hole measurements between pairs or sets of holes will be developed. Later in the program, when tunnel rock fragmentation machinery is more clearly defined, research will be directed toward incorporating logging measurements in long hole drilling equipment that may be made an integral of the excavation system.

Major Accomplishments: A well logging system for making measurements of physical properties of rock penetrated by vertical drill holes was designed and partially developed by adapting on-hand Bureau of Mines equipment to special needs of geological-hydrological prediction problems associated with tunneling at depths of several thousand feet in hard rock. Calibration

holes and models were developed for providing a means of improved quality control required for the quantitative measurements of interest. A new interpretive technique for determining P- and S-wave velocities from acoustic logs was developed and preliminary tests were performed to evaluate its effectiveness.

PREDICTION OF GEOLOGIC AND HYDROLOGIC CONDITIONS AHEAD OF RAPID EXCAVATION OPERATIONS

I. Introduction

The objective of this research project is to develop new or improved geophysical well logging and cross-hole measurement techniques for detecting, delineating, and evaluating geologic and hydrologic conditions at depths of several thousand feet in hard rock in advance of a rapid excavation tunneling project. Measurements of interest fall into two categories: (1) those made in vertical holes drilled from the ground surface to the depth of the tunnel, and (2) those made in underground horizontal holes drilled ahead of a tunneling machine (1). The present research is directed toward the first category in which geophysical logging measurements are made in vertical holes to assess the physical characteristics of rock in the immediate vicinity of the borehole. In addition to continuing these studies, research in the next year of the project will be directed toward cross-hole measurements that will make it possible to investigate the much larger volume of rock existing between pairs or sets of drill holes.

Later in the program, when the tunnel excavation system is more clearly defined, attention will be devoted to measurements of the second category in which geophysical logs will be made in horizontal holes drilled ahead of the tunneling machine. Inhole geophysical measurement techniques in both categories are urgently needed for making accurate predictions of geologic and hydrologic conditions ahead of a rapid excavation tunneling system. Reliable knowledge of these conditions will make it possible to avoid

expensive or disastrous surprises and to keep the tunneling machinery operating at peak efficiency under the varying geologic conditions that can be expected to occur along the route of a tunnel.

II. Technical Discussion

Unknown or poorly defined geologic and hydrologic conditions, probably more than any other factor, will determine the degree of difficulty and the cost of excavating and supporting underground openings created by rapid excavation methods for military applications. Natural features such as unusual hydrologic conditions, zones of intense fracturing and changes from one rock type to another, together with manmade features such as abandoned mine workings and uncharted oil, gas or water wells, constitute hazards that may threaten men and equipment and greatly affect the efficiency of future rapid excavation tunneling systems. The rock in the vicinity of these hazards can be expected to be characterized by anomalous physical properties that, if measured by inhole techniques, will provide sufficient warning to allow time for evading the hazard or for planning how to cope with successfully. Some of the physical properties that are considered to be diagnostic of hazards are: acoustic velocity and attenuation, elastic moduli, electrical resistivity, bulk density, fracture intensity, magnetic susceptibility and temperature. Tools and techniques are being developed to measure and interpret these properties in terms of the hazards that they represent.

III. Research Plan

During the first year of research just completed, emphasis was placed on developing a geophysical well logging capability for measuring physical properties that are diagnostic of hazardous conditions in tunneling. Logging

equipment that had been developed under previous Bureau of Mines programs for mining applications was modified and adapted for specific application to rapid excavation tunneling problems. Techniques of data acquisition and preparation for computer analysis were streamlined. Quantitative accuracy of measurements was improved by reducing instrument drift and developing calibration models and standards for quality control of measurements. Preliminary studies were made to develop computer techniques for analyzing acoustic log waveformed to reduce the adverse effects of human judgement in determining the transit time of first arrivals of compressional and shear wave energy.

Research in the coming year will lead to the development of a mobile field logging instrumentation system that will be tested and evaluated for determining physical properties of rocks penetrated by drill holes along the route of a tunnel. Initial studies will also be made of techniques for enlarging the sample volume of rock to be evaluated by making measurements between pairs or sets of drill holes by use of the mobile instrumentation system. Finally, when rapid excavation tunneling machinery is more clearly defined later in the program, research will be directed toward developing a logging system that will be operational in horizontal holes drilled ahead of the tunnel face. The logging system will be designed to be as compatible as possible with the tunneling machinery, with the final goal of incorporating the logging instrumentation in the long hole drilling equipment which may be made an integral part of the fragmentation system.

IV. Results to Date

A measurement system has been defined for making inhole and between-hole geophysical measurements for assessing the minability and strength characteristics of rock ahead of the construction of a tunnel by rapid excavation techniques.

Early in the project a review of previous research was made which indicated that acoustic and electrical measurements can be expected to be most diagnostic of minability characteristics (2). Consequently, the system will be designed to make these two key measurements in individual holes and also between adjacent holes. The following additional measurement capabilities have been identified as desirable and are being developed for use in individual holes only: Bulk density, porosity (by measuring water content in pores and fractures), fracture intensity, caliper, magnetic susceptibility, and temperature (3, 4).

Logging equipment including probes, a cable hoist mechanism, a chart recorder, and surface electronic control modules, that were previously acquired by the Bureau of Mines for application to mining problems, have been adapted for use in ARPA tunneling research. A laboratory test tank has been developed for evaluating the performance of probes at elevated temperatures expected at depths of 5,000 feet (120° - 170°F). In some cases, probes will require modification or redesign to reduce temperature drift to acceptable levels.

The Bureau of Mines logging equipment on hand is being installed in a heavy duty mobile unit capable of carrying the extra weight associated with deep

logging requirements. The new mobile unit, to be developed with ARPA funds, has been designed, and bids for van construction have been solicited.

A need has been identified for improving the reliability of determinations of P- and S-wave velocities from acoustic log measurements. Presently available commercial methods are handicapped by requiring human judgement to pick the onset of P- and S-wave arrivals on variable-density or wiggle-trace displays of acoustic waveforms. In critical cases of intense fracturing when signal amplitude is greatly reduced, the results of human analysis are highly questionable. A new technique for picking P- and S-wave arrivals, which does not require human judgement and therefore is free of human error, has been conceived, developed and tested with synthetic waveform data. Results indicate that the onset of both P- and S-waves can be detected by the new method with greatly improved reliability and accuracy, even in the presence of noise of the same magnitude as the signal. Additional tests of the method are being made with real waveforms acquired by use of a special 3-receiver acoustic probe recently added to the Bureau of Mines logging system. An example of the results of these preliminary tests is shown in figure 1. The figure shows a computer plot of the cross-correlation function generated with a pair of sliding velocity "boxcar" windows 30 microseconds wide with Hanning-tapered edges flared to a base width of 45 microseconds (5, 6). The windows are moved down the receiver waveforms as the cross-correlation is computed so that irrelevant data representing velocities beyond the window limits are excluded. The first two major peaks of the cross-correlation function represent the time lags associated with P- and

S-wave arrivals at two of the receivers on the probe. Velocity is computed from the lag time peaks by simply dividing the physical spacing between the receivers on the probe by the lag time.

The technique will be tested further with additional waveforms that will be obtained for a variety of rock types with associated fracturing of varying intensity. Digital equipment for streamlining the acquisition and preparation of acoustic waveform data for computer analysis has been specified and placed on order. If tests of the data acquisition and off-line computer analysis techniques are successful, a future effort to provide real-time data processing in the field might be justified and desirable. Preliminary assessment of this novel technique for determining P- and S-wave velocities suggests that it may constitute a major breakthrough in velocity log analysis with probable future spin-off benefit to petroleum and engineering logging interests. Therefore, we propose to publish a complete description of the technique when it has been sufficiently developed and tested to assure accurate appraisal of its advantages and limitations.

Another important aspect of quantitative analysis of geophysical logs that is often underemphasized is accurate calibration of equipment. This need is especially critical for logging measurements of rock properties that are to be used in collaboration with other methods separately calibrated (e.g. laboratory or in-situ compressive strength measurements). We have developed two independent means of testing and calibrating logging equipment.

First, a series of five test holes penetrating a variety of different rock types were developed in the vicinity of Denver. Two test holes were drilled in sedimentary rock, one at the Denver Federal Center and the other near the Ralston Reservoir north of Golden, Colorado. Arrangements were made for access to three additional test holes in very hard granitic rock near Raymond, Colorado. These hard-rock test holes were drilled by NOAA (Boulder Laboratories) and were made available to us by that agency. The five test holes penetrate rock types that represent broad range of geological conditions that should be considered in pre-tunneling assessment studies. Rock cores for laboratory tests are available from holes at both sites.

Second, we have designed and constructed, with partial support from ARPA funds, a set of full-scale concrete models for calibrating density, magnetic susceptibility and sonic velocity logging probes. Table 1 gives the design specifications and physical properties of special blends of concrete used to construct the models.

TABLE 1. - Geophysical Logging Calibration Models -

Design Specifications and Physical Properties

Model	Size and Shape	Hole Diam. (in)	Bulk Density (g/cc)	Magnetic Susceptibility (cgs units)	Acoustic Velocity (ft/sec)	Total Water Content Free and Combined (volume percent)
1	Solid cylinder	3	1.70	605×10^{-6}	12600	26
	diameter 4 ft					
	height 8 ft					
2	Rectangular block	2	2.36	1685×10^{-6}	13500	21
	length 13.5 ft	3	2.36	1685×10^{-6}	13500	21
	width 4 ft	5	2.36	1685×10^{-6}	13500	21
	height 8 ft	8	2.36	1685×10^{-6}	13500	21
3	Solid cylinder	3	3.06	9090×10^{-6}	*___	28
	diameter 4 ft					
	height 8 ft					

* Laboratory measurements in progress.

The models were constructed by pouring carefully blended mixes of concrete into subsurface pits excavated for that purpose at the Denver Federal Center. Subsurface construction has several advantages over construction above the ground, including easy access, low cost, good foundation stability, weather protection, and reduction of radiation leakage for neutron and gamma-gamma log calibration.

Model Number 1 was made with low density aggregate concrete with approximately 0.2 percent (by volume) magnetite added.

Model Number 2 was made with standard concrete containing approximately 1 percent magnetite (by volume). This model contains 4 holes with different diameters which will be used to determine empirical corrections for hole diameter effects. Hole diameter corrections are especially important for certain types of slim-line radiation logging probes which can not be heavily shielded or callimated because of physical space constraints.

Model Number 3 is constructed with concrete containing a high percentage of hemetite to provide the desired high value of bulk density. Approximately 5 percent magnetite (by volume) was added to the mix to provide high magnetic susceptibility.

A supply of water, electrical power, a pump, and tanks for mixing simulated drilling mud are available at the sit of the models so that the test holes may be filled with water, mud, or they may be emptied to determine empirical corrections for hole-filling medium.

A report is in preparation describing the design and construction of the calibration models, and the detailed results of laboratory analyses of samples that were obtained to determine the physical properties.

Calibration tests of Bureau of Mines logging equipment modified for ARPA research will be made in the coming project year, and results will be described in future semiannual or annual reports.

REFERENCES

1. Hibbard, R. R. and others, Hard Rock Tunneling System Evaluation and Computer Simulation -- Semiannual Technical Report. General Research Corporation, Arlington, Va., September 1971, pp. 34-35.

2. Scott, J. H. and others, The Relationship of Geophysical Measurements to Engineering and Construction Parameters in the Straight Creek Tunnel Pilot Bore, Colorado. Int. Jour. Rock Mech. Min. Sci., V. 5, No. 1, January 1968, pp. 1-30.

3. Pirson, Sylvain J., Handbook of Well Log Analysis. Prentice-Hall 1963, 326 pp.

4. Zablocki, C. J. and Keller, G. V., Borehole Geophysical Logging Methods in the Lake Superior District. Seventh Annual Drilling Symposium Transactions, University of Minnesota, October 1957, pp. 15-24.

5. Bracewell, Ron, The Fourier Transform and its Applications. McGraw-Hill 1965, 381 pp.

6. Blackman, R. B., and Tukey, J. W., Power Spectra. Dover 1958.